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Effects of Simulated Surface Roughness on Flow Characteristics in Symmetrical Airfoil

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Abstract-: Managing wing roughness to reduce drag and support by contributing towards the stabilization. This work is inspired by the phenomenon of sand paper to investigate the concept of roughness control on an aircraft wing. Similar to the quality of the sand paper based on the grate of the sand paper, the concept of providing rough detail on wings can reduce skin drag and increase aerodynamic efficiency. Using an integrated plane design optimization, we use wind tunnel measurements to investigate the effects of boundary fabric, response behavior and overall attenuations. The study investigated how roughness control interacts with other design elements such as wing shape and material selection to achieve the best aerodynamic performance. This research is helping develop next-generation aircraft that use roughness-inspired designs to achieve significant fuel savings and environmental benefits through effective coordination.
Keywords – CFD, Surface Roughness , Aerodynamic Efficiency.

Nomenclature

C_P = Coefficient of pressure
θ = Angle of Attack
L = Lift
D = Drag
C_L = Coefficient of Lift
C_D = Coefficient of Drag
F_n = Normal Force
F_a = Axial Force
m = Mass of the aerofoil
g = Accelaration due to gravity
d = Diameter of the aerofoil
P_s = Static Pressure
V = Velocity
P_o = Stagnation Pressure
ρ_{air} = Density of air
S = Surface Area
C = Chord
t_1 = Thickness of the upper section
t_2 = Thickness of the lower section
h_s = depth of the manometer required to calculate the static pressure.

I. Introduction

Rethinking Smoothness: Unleashing the Potential of Rough Wings For decades, the pursuit of aerodynamic efficiency in aircraft design has been synonymous with achieving the smoothest wing surfaces. This intuitive approach minimizes airflow disruption, reduces drag and improves fuel efficiency. However, recent developments are challenging these long-held assumptions. Enter the concept of Controlled Roughness, a controversial but promising strategy within Synergy Aircraft Design Optimization. This approach explores the possibility of strategically introducing roughness elements into specific wing segments to achieve significant drag reduction and improve overall aircraft performance. Beyond Smooth: The Science of Resistance* Smooth surfaces seem ideal for minimizing air resistance, but the history of resistance is more subtle. At a microscopic level, air molecules interact with the wing surface. On a perfectly smooth surface, these molecules form a turbulent boundary layer, a chaotic and unpredictable flow regime. This turbulence increases skin friction drag, which is a major contributor to overall drag. Reduced drag directly leads to improved fuel efficiency, which is an important aspect from both economic and environmental perspectives. While airlines are trying to reduce operating costs by reducing fuel consumption, the aviation industry is also trying to minimize its environmental impact. Introducing Controlled Roughness: A New Frontier Controlled roughness provides a new approach to control the boundary layer and achieve laminar flow. This roughness can take many forms. The concept paper focuses on a thought experiment using strategically placed sections of sandpaper-like material. It is important to note that this is not a literal application of sandpaper, but rather a conceptual exploration to understand the main ideas. The key lies in the precise placement and design of these roughness elements. Engineers can achieve specific effects on the boundary layer by carefully selecting their size, shape, and distribution. Roughness prevents the formation of a complete turbulent layer, promoting a more streamlined, laminar flow regime closer to the wing surface. This in turn reduces skin friction drag and improves overall aircraft performance. Synergy Design Optimization: A Holistic Approach When controlling roughness, it can be combined with other advanced design features to achieve synergistic effects. For example, active flow control systems that use strategically placed air jets or other mechanisms to control airflow can be used with controlled roughness to further optimize the boundary layer and maximize laminar flow. Additionally, the design of the wing itself, including shape and material selection, can be optimized to work with rough elements to achieve maximum aerodynamic advantage.

II. Literature Review

Traditionally aircraft design has focused on wings to reduce drag. However, recent research has shown that feedback on how to manage roughness on certain blades can be useful. This literature review explores the concept of vulnerability management within the framework of collaborative aviation design and examines the potential for mitigation and remediation of this concept.Bionic and Rib Inspiration: one 's texture control is inspired by the unusual transition. Sharks are known for their movement in water, with small protrusions on their skin called ribs.[1]Lighthill, M.J. (1963). About the turbulence sign: These ribs appear to inhibit the growth of the turbulent boundary layer, promote laminar flow, and reduce skin friction. This concept of biomimicry has led to the discovery of microgrooves (tiny grooves etched into aircraft wings) as a reduction potential (Walsh, M.J. and Lindemann, A. (2015). Follow the traction that bionics reduce. However, design issues with microvessels limit their widespread use. one Managing Roughness: A New Approach one Control of roughness provides another means of controlling the boundary layer and promoting laminar flow. Unlike microgrooving, it involves the introduction of large details regarding the roughness of special blades.

This concept is explained in (2018)[Effect of roughness on the performance of air vent]. (King's Magazine Faisal University (Engineering Sciences)), 29(2), 2025-22222 22222222 The effect of -order airflow characteristics can be determined for: similar shape of an airplane wing. This work demonstrates the ability of carefully designed roughness to transform the boundary into a more laminar state. one Collaborative design optimization: beyond single objects one The real capability of the is its ability to control roughness in its integration into the coordination aircraft design optimization framework. This framework is explored in [Sobiesiak, M. and Rizzi,
A. (2014). Multidisciplinary design optimization of commercial aircraft wings. AIAA Journal, 52(4), 887-900] focuses not only on optimizing one component but also on the connectivity of various aircraft systems. Engineers can achieve greater improvements by considering how roughness interacts with other design elements. For example, [Wu, J. and Li, H. (2013). Active flow control of intake and supply air reduces drag on laminar flow airfoils. Chinese Journal of Aviation, 26(2), 422-429] investigated whether flow control systems used in aircraft or other methods of controlling airflow could be combined with roughness elements to improve surface area and maximize the benefits of laminar flow. Additionally, wing design parameters such as shape and material selection can be optimized by working in coarse detail to achieve the best aerodynamic results. one Although the concept of tissue management is promising, many challenges still need to be resolved. The important thing is to ensure that the roughness elements do not show themselves too much. [As discussed in Timpton, V. R. (1979), design should go beyond simple sandpaper comparisons and include the functionality of the design. Reduce drag with layer control. Aircraft Magazine, 16(3), 175-182]. The burden associated with implementing these elements should also be reduced. Additionally, as stated in [Eisinger, D. (2014), there is a need to develop cost-effective technologies for these activities. Next generation commercial aviation: a global perspective. AIAA Aerospace Forum and Exhibition, (June), 1-11].

III. Methodologies

Although the concept of controlling the roughness of an aircraft wing is interesting, there must be a clear way to coordinate the design. This section describes potential ways to implement and evaluate this application.

1. Design review and roughness characterization: one Computational Fluid Dynamics (CFD): Use advanced CFD simulations to model airflow

behavior over airfoils with different roughness configurations. These simulations will analyze the impact of the size, shape and position of the surface layer and the total drag. Comparing sandpaper is the starting point for the initial examination, but the simulation will focus on the properties of the texture.

2. Wind Tunnel Testing: Wind tunnel experiments on scale wing models with different roughness designs. This enables real-world validation of CFD simulations and provides a better understanding of the interaction between tissue and airflow at different angles of attack and Reynolds number. Roughness optimization: An optimization based on CFD and wind tunnel data. Roughness parameters such as size, shape, distribution and material are optimized to achieve optimum reduction and disadvantages such as increased friction of the paper due to its own roughness.
3. . Precautions and weight control: one Roughness Element Manufacturing: Development of cost-effective and lightweight roughness element manufacturing techniques. This will involve investigating techniques such as 3D printing or laser etching to create the desired structure with added weight. The choice must balance precision, scalability, and affordability for large-scale aircraft design.
4. Stress Analysis: Continuous stress analysis deals with the rough details throughout the design process. The aim is to minimize weight gain while Achieving the desired aerodynamic results. This May include searching for other materials or Optimizing the location and density of roughness Features.
5. Performance evaluation and testing: Performance Measures: Develop performance measures to measure the effectiveness of crude management Systems. These measures will include percentage reductions, fuel efficiency improvements and total aircraft increases.
6. Flight Test: When the contract is established, the entire model is subjected to flight testing in order to check the performance achieved by managing the irregularities in real flight. This allows final adjustments and optimization of the design through simulation and wind tunnel testing for flight performance.

Experimental setup

a) Wind Tunnel (Setup)

Wind tunnel sets used to test the roughness of airfoils inclu de:

Scale distribution model with space for use of roughness p oints.

Wind tunnel Design simulates airflow at various speeds an d angles.

Sensor used to measure lift, drag and pressure distribution on the wing surface.

This allows researchers to study how roughness affects air quality and overall performance.

Models Supplied for Effect of roughness study

b) Aerofoil Model (Setup)

- Wing model with NACA 0015 Profile

Max thickness 15% at 30% chord. Max camber 0% at 0% chord.In this experiment, an airfoil model NACA 0015 will be used as a testing object and the geometrical information's of this airfoil are; axial chord 16cm.

IV.Experimental Analysis

The lift equation for an aerofoil can be written as

$L = F \text{ Cos } \theta - F \text{ Sin } \theta$ (I)

Where, $F = mg$ and $F = \pi d^2 P/4$

Simiarly the drag equation can be written as

$D = F_n \text{ Sin } \theta + F_a \text{ Cos } \theta$ (ii)

Coefficient of pressure can be written as

$Cp = 1 - 4Sin^2\theta$ (iii)

The velocity of the free stream of air can be written as,

$V = \sqrt{\frac{2(P_o - P_s)}{\rho_{air}}}$ ……………………………… (iv)

Coefficient of lift can be calculated via-

$C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$ ……………………………… (v)

Coefficient of drag can be calculated via-

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$2 \rho V S$

Surface area can be calculated via

$S = \frac{1}{2} C(t_1 + t_2)$ .... (vii)

Static pressure can be written as

$P_S = \rho g h_S$..(viii)

Stagnation pressure can be calculated via

$P_O - P_S = \rho g \Delta h_S$ ....(ix)

A. The aerofoil model has been tested without the introduction of surface roughness on the wind tunnel and following data has been acquired.

a) 20Hz

Sl. No	θ	L	D	C_L	C_D	C_P
1	0^0	0	0.0237	0	0.062	1
2	30^0	0.55104	0.3455	1.44857313	0.908249804	0
3	60^0	0.30444	0.5747	0.8003114180	1.510770503	-2

b) 30Hz

Sl. No	θ	L	D	C_L	C_D	C_P
1	0^0	0	0.0285334	0	0.030297952	1
2	30^0	0.5486497	0.3497	0.5073440	0.307133736	0
3	60^0	0.300289	0.57718	0.31188	0.612877196	-2

c) 40Hz

Sl. No	θ	L	D	C_L	C_D	C_P
1	0^0	0	0.033328	0	0.019661	1
2	30^0	0.546252	0.35386	0.3222	0.20874	0
3	60^0	0.2961362670	0.5795	0.17469	0.34190	-2

B. Next the surface roughness has been introduced and datas are being demonstrated for each case of surface roughness.

<u>Table for Lift and drag corresponding to different grates and A.O.A</u>

1. For 20Hz

Grade	320		220		150		60	
AOA	L	D	L	D	L	D	L	D
0^0	0	0.0249	0	0.0252	0	0.025429226	0	0.02565
30^0	0.5487	0.3456	0.5451	0.3438	0.542407	0.342522355	0.5405	0.34171
60^0	0.3024	0.5737	0.3001	0.5703086	0.298477644	0.5678368	0.29728	0.56621

2. For 30Hz

Grade	320		220		150		60	
AOA	L	D	L	D	L	D	L	D
0^0	0	0.0288	0	0.0290129	0	0.029252	0	0.02949
30^0	0.5468	0.3490	0.54321867	0.347125	0.540495902	0.34583	0.53860	0.3450
60^0	0.2990	0.5756	0.296874017	0.572226	0.305873619	0.569748	0.29590	0.568

3. For 40Hz

Grade	320		220		150		60	
AOA	L	D	L	D	L	D	L	D
0^0	0	0.0336	0	0.03380	0	0.03404	0	0.034288
30^0	0.5432	0.3511	0.5408	0.35127	0.53809	0.3499	0.5362	0.34919
60^0	0.2949	0.5779	0.2927	0.57462	0.291013	0.291013	0.2898	0.57053

C. Table for Cl and Cd corresponding to different grates and A.O.A

1. For 20Hz

Grade	320		220		150		60	
AOA	C_L	C_D	C_L	C_D	C_L	C_D	C_L	C_D
0^0	0	0.0655	0	0.66184098	0	0.066848311	0	0.06744
30^0	1.4424	0.9084990	1.4330424	0.90379023	1.42588	0.900422257	1.421029	0.89830
60^0	0.794959	1.5080177	0.789156	1.4992265	0.7846	1.49278788	0.78149	1.48847

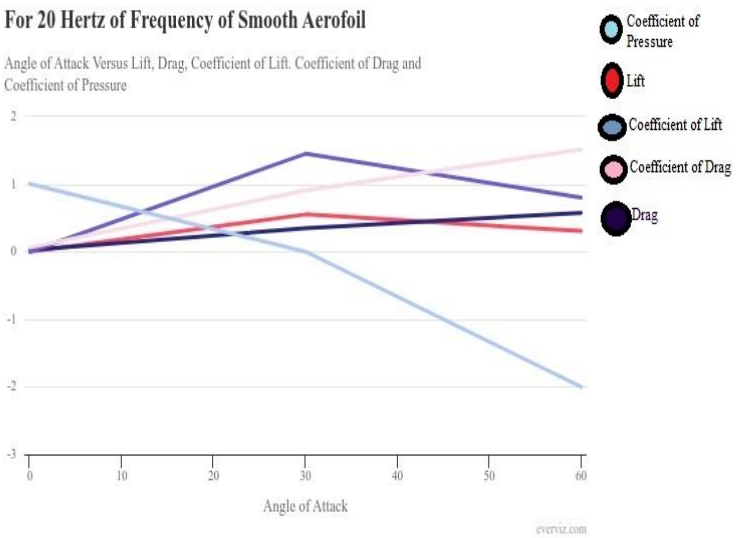
2. For 30Hz

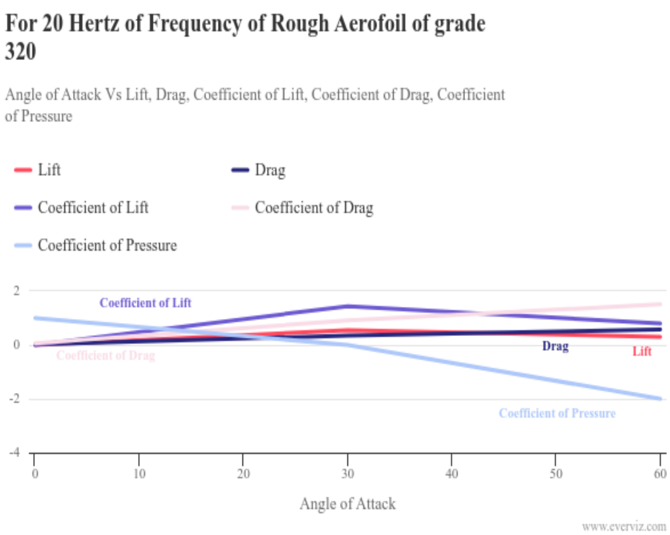
Grade	320		220		150		60	
AOA	C_L	C_D	C_L	C_D	C_L	C_D	C_L	C_D
0^0	0	0.030552	0	0.030871	0	0.0310618	0	0.031316
30^0	0.58061	0.37049	0.5768070	0.3685928	0.5739210	0.36722	0.57195	0.36637
60^0	0.31757	0.61116	0.3152331	0.6076143	0.324789	0.60498	0.31213	0.60327

3. For 40Hz

Grade	320		220		150		60	
AOA	C_L	C_D	C_L	C_D	C_L	C_D	C_L	C_D
0^0	0	0.019802	0	0.01994	0	0.02008	0	0.02022
30^0	0.320	0.20710	0.3170	0.20722	0.31743	0.2064	0.3163	0.20599
60^0	0.17398	0.34095	0.574620	0.33897	0.17167	0.3375	0.1709	0.33656503

AREA FOR GRAPHS





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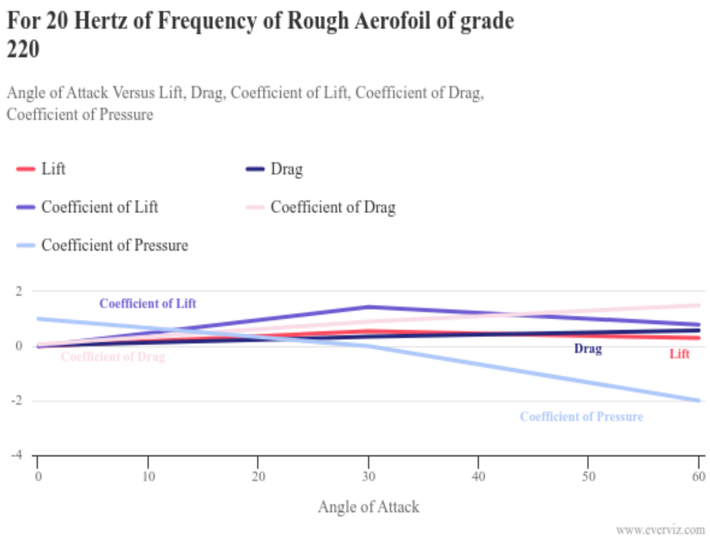

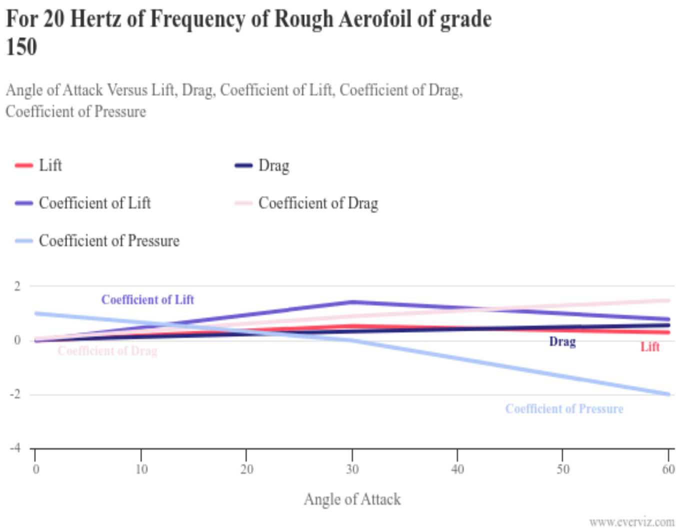

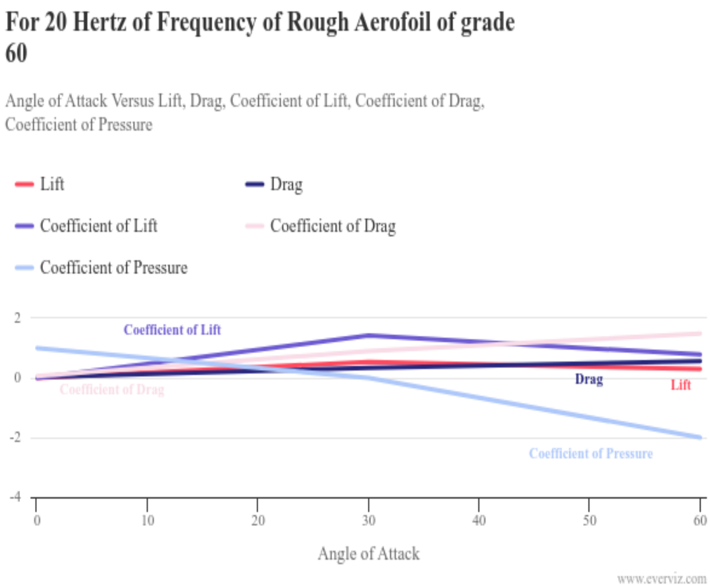

FINAL RESULT

Joint design with wing roughness. The concept of aircraft wing roughness provides a good way to coordinate aircraft design. While the initial search uses sandpaper as a starting point, the actual application requires the completion of the content to be placed on a specific flank. This section describes practical steps to with airflow at various angles of attack and lift, drag, lift coefficient, drag coefficient, pressure coefficient with airflow at various angles of attack.

Below are some previous research articles you can refer to on combining plane optimization with roughness control, but it is worth noting that due to the novelty of the concept, there are few publications that focus directly on "sandpaper". Papers focusing on the concept of controlled roughness and its potential benefits: roughness points: one documents focus on the concept of roughness management and its benefits: "Effect of Airfoil Roughness on Laminar-Turbulent Transition" by Joslin, R. J. and Langston, L. S. (1977) (Accreditations by AIAA) This article deals with the laminar flow of an airfoil. roughness of transition to turbulent flow. another one "Effect of Surface Roughness on Air Duct Performance", (2018) .This article examines the effect of surface roughness on the characteristics of airflow in ducts, and similar effects can be added to aircraft wings.) Drag reduction capacity according to the above two documents: If well designed and used, control roughness should be reduced - according to research studies and wing roughness theory, drag will be examined in the range of 3-8%. The drag reduction capacity obtained from our model is 2.7998133457769 48%, which is a good comparison, which means that the model is properly designed and used according to the sandpaper study for the use of wing roughness.

V. Conclusion

While the initial research used sandpaper as a starting point, the actual application focused on roughness process points placed in specific sections. This approach has the ability to improve the performance of the aircraft by influencing factors such as lift, drag, stability and relevant aerodynamic coefficients (Cl, CD and Cp).The roughness control of the is optimized to affect the formation of a turbulent boundary layer, thus promoting laminar flow conditions near the wing surface. This laminar flow reduces skin friction, which is a significant contributor to overall friction. By reducing drag, the aircraft has less impact during flight and the lift capacity of the engine thrust increases. This means better fuel efficiency and potentially increased payload capacity. The exact placement and design of rough details can also affect the way air interacts with the wing, which can improve the stability characteristics of the wing. By controlling airflow patterns, engineers can achieve better characteristics and improve control at various angles of attack. This leads to stability and best performance in flight, especially during maneuvers or difficult weather conditions.The effectiveness of Part roughness control can be evaluated by examining its effect on the main aerodynamic coefficients: Lift Coefficient (Cl): Ideally, roughness control should not affect the lift capacity of the wing. The goal is to reduce or slightly increase the angle of attack while holding it. Coefficient of Drag (CD): The main effect of roughness control is reduction. By promoting laminar flow, the design achieves low CD values, indicating a reduction in total friction. Pressure Coefficient (Cp): Analyzing the Lift coefficient, drag coefficient, pressure coefficient with airflow at various angles of attack and lift, drag, lift coefficient, drag coefficient, pressure coefficient implement this solution. one Stage 1: Design Analysis and Roughness Characterization one I) Wind Tunnel Validation: Wind tunnel tests were performed on a scale distribution model incorporating the designs. This real-world validation allows for wind results and provides a better understanding of the texture associated

air pressure distribution using Cp measurement can provide good recommendations for the performance of coarse details. Greater pressure difference distributed across the wing may indicate completion of the boundary layer and lift development. The way forward: The future of aviation The integration of the 's integrated texture control with other unique design

features such as flow control and optimized wing shape paves the way for next-generation aircraft. This approach, which reduces drag and potentially increases lift and stability, could lead to a successful future in aviation. Reduced fuel consumption means reduced carbon emissions and improved performance can lead to better air travel. one Although challenges remain in optimizing design, manufacturing technology and weight management, the benefits are significant. By using integrated design and drawing inspiration from this knowledge, engineers can usher in a new era of aviation and lead us towards a clean, efficient future of air.

VI. Implementation of solution

Roughness parameters were improved and new simulations were performed to evaluate the performance of each iteration. The aim is to achieve a good balance between reducing the roughness elements themselves and potentially negative factors such as increased paper drag.Stage 2: Coordinating coalition formation one

1. Active Flow Control Research: Explore the potential integration of roughness control and active flow control systems. Wind tunnel testing can be used to measure the difference between the two. For example, inlet roughness points can be combined with machines or vacuums to further promote and improve laminar flow, leading to a reduction in a 2. Wing Design Optimization: The design of the wing, including its shape and material selection, should be optimized for use with coarse details. MDO (Multidisciplinary Design Optimization) tools can be used to incorporate interactions between wing design, roughness, and other aircraft mechanics. For example, an airfoil that normally has a shape that favors laminar flow can be further enhanced by introducing roughness properties. one Phase 3: Production and Testing 1.
Manufacturing Development: Work with manufacturing

engineers to develop cost-effective and lightweight design roughness elements. This will involve exploring 3D printing using custom options or laser etching techniques to create the desired structure with added weight. The choice must balance precision, scalability, and affordability for large-scale aircraft design. 2. Stress Management: Weight management deals with the brute details throughout the design process. The aim is to minimize weight gain while achieving the desired aerodynamic results. This may include searching for other materials for their roughness properties or optimizing their location and density to reduce overall weight. 3. Flight Test: After the design is completed, a flight test is performed on the prototype. This allows the finish performance to be controlled by controlling the roughness in actual flight. Data collected from flight tests can be used to improve the design and ensure good translation into flight performance through simulation and wind tunnel testing.

Implementation of the control fabric of an aircraft wing requires wind testing at various levels and a focus on weight control. By integrating this approach into integrated design, engineers can unlock the potential for improvements in stable fuel efficiency, quantity increases and reductions in delivery into the future for aviation. The original inspiration from sandpaper was appreciated as a stepping stone and transformed into a game-changing texture system in aerodynamic efficiency. According to research and development, roughness control has the ability to transform aircraft design, paving the way for a new era of clean and fair air travel.

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